Behavior of a High Current Vacuum Arc Between Hollow Cylindrical Electrodes in a Radial Magnetic Field

RAYMOND L. BOXMAN, SENIOR MEMBER, IEEE, ELI GERBY, AND S. GOLDSMITH

Abstract—Experimental observations were conducted on the behavior of a high current vacuum arc on cylindrical electrodes in a radial magnetic field. The arc was sustained between the ends of two cylindrical Cu electrodes, 54-mm diam and 1.5-mm wall thickness separated by 5 mm. Arc current pulses with peak values in the range 4-15 kA with a half amplitude full width (HAFW) duration of 8 ms were investigated with radial magnetic fields proportional to the instantaneous current with proportionality constants of 4.0 and 6.5×10^{-6} T/A. The arcs were photographed simultaneously with a streak camera and by a high speed framing camera and the arc voltage was recorded on a digitizing transient recorder. The results indicated that the arc in this geometry, both with and without an imposed radial magnetic field, can be characterized by three development stages: a) arc formation, b) diffuse arc along the electrode perimeter, and c) simultaneous existence of several concentrated arc columns. When a radial magnetic field was imposed two changes were noted: 1) the arc appeared somewhat more distributed in that a greater number of constricted columns were observed, and they were distributed more evenly; and 2) the constricted columns moved in the $\bar{J} \times \bar{B}$ direction with velocities in the range 5-35 m/s.

I. INTRODUCTION

THE MOST EXTENSIVE application of vacuum arcs is as a switching medium in vacuum switches. In order to control the deleterious effects of anode spot formation, many high current vacuum switches utilize a petaled contact structure which generates a magnetic field, generally directed in the radial direction, which pushes the arc around the periphery of the contact. While this principle has been applied successfully in practice, relatively few observations on the interaction of a high current vacuum arc in the presence of a transverse magnetic field have been published, and specifically no detailed observations on electrodes having a surface geometry-magnetic field combination similar to those found in commercial devices utilizing this principle have been published.

In this paper preliminary observations on the behavior of a vacuum arc between cup electrodes, both with and without the imposition of a radial magnetic field, will be reported. The cup geometry was chosen to allow the peripherial motion and radial magnetic field expected on petaled electrodes used in commercial devices, but allowing the generation of a more controllable, measurable, and calculable magnetic field. Magnetic field strengths similar to those existing in commercial devices were used, and a thin cup wall was chosen to increase the current density in order to simulate the high current present in commercial devices.

Manuscript received March 20, 1980; revised June 30, 1980.

R. L. Boxman and E. Gerby are with the Department of Interdisciplinary Studies, School of Engineering, Tel Aviv University, Tel Aviv, Israel 69978.

S. Goldsmith is with the Department of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel 69978.

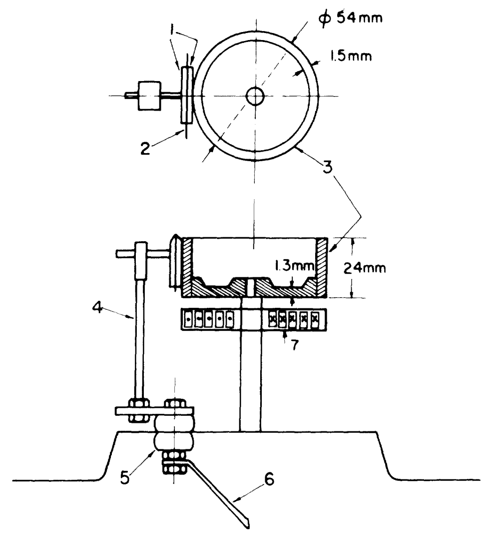

Fig. 1. Construction of trigger assembly, cathode, and spiral coil: 1) Cu sheets, 2) microscope slide cover slip, 3) cup cathode, 4) attaching screw, 5) feedthrough, 6) electrical connection, and 7) spiral coil, connected electrically in series with cup electrode. Anode assembly similarly constructed but consisting of parts 3) and 7) only.

II. EXPERIMENTAL APPARATUS AND PROCEDURES

The arc was sustained between two Cu hollow cylindrical cup electrodes, 54-mm OD, 1.5-mm wall thickness, 24 mm high, and separated by 5 mm (Fig. 1). A trigger assembly consisting of two Cu sheet electrodes ($10 \times 15 \times 1$ mm) separated by a microscope cover glass slip ($25 \times 25 \times 0.1$ mm) was held in place tangential to the cathode, approximately 1 mm below its surface, by pressure from a screw attached to the trigger feed assembly, which provided electrical connection to the trigger anode as well. The electrodes were fabricated from technical grade Cu and then were degreased in acetone, cleaned in nitric acid and rinsed in water prior to mounting in the vacuum system.

The radial magnetic field was generated by a pair of 5-turn spiral coils (Fig. 1). Each coil was located on one of the electrode support rods and connected electrically in series with the corresponding electrode. The electrode base and walls were sufficiently thin so that the magnetic diffusion time was

0093-3813/80/1200-0308$00.75 © 1980 IEEE

short (17 μs) in comparison to the current pulsewidth (8-ms HAFW). Thus the magnetic field was proportional to the instantaneous current. Each coil produced a magnetic field generally directed towards the interelectrode gap. At the gap midplane the opposing axial components cancel while the radial components add, producing a purely radial field. The amplitude of the radial field could be controlled by varying the axial position of the coils. The magnetic field strength was determined by inserting a shorting slug between the electrodes, flowing a 50-Hz 10-A current in the electrode-coil circuit and measuring the voltage induced on a sensing coil placed in the gap opposite the rim of the electrodes. Subsequent experiments were performed either at 4.0 or 6.5×10^{-6} T/A or without any external magnetic field.

The electrodes and field coils were located in a 16-cm diam stainless steel vacuum chamber. The anode was connected to the pulse circuit via a feedthrough at the top of the chamber; the cathode was connected to the base of the chamber, and the return current flowed in the chamber wall to the top where it was connected to the pulse circuit. Thus with the exception of current flow in the immediate vicinity of the coils and electrodes, current flow in the chamber was generally coaxial. The chamber was pumped by an oil diffusion pump equipped with an integral water-cooled baffle. The effective pumping speed of the entrance to the arc chamber was approximately 50 l/s. The ambient pressure was approximately 2×10^{-5} torr, and was limited by outgassing from the potting material used in constructing the field coils. The chamber was fitted with three ports for visual or photographic observation at the plane of the electrodes.

The arc current pulses were formed in an *RLC* series circuit. Taking into account stray components, the equivalent values of the circuit elements were 18 mΩ, 23 μH, and 0.336 F. The circuit was thus overdamped. The capacitor bank was electrolytic, and could be charged up to 450 V; peak current was varied by varying the capacitor charge voltage. The arc current waveform for a charge voltage of 200 V is that of an overdamped *RLC* circuit and is shown in Fig. 2. The arc was initiated by first charging the capacitors to the desired voltage and isolating the charging circuit, and then applying a trigger pulse from a separate circuit to the trigger electrode. The trigger pulse, initially about 1.5 kV, caused a breakdown between the trigger electrodes across the edge of the thin glass separator, and formed cathode spots on the trigger cathode, which was electrically and mechanically connected to the main cathode. The trigger mechanism is similar to that determined by Boxman [1]. Either the arc voltage, measured with a 1000:1 probe, or the arc current, measured with a Rogowski coil and operational amplifier integrator circuit, could be recorded on a digitizing transient recorder synchronized by an auxiliary output of the trigger circuit.

The arc was photographed simultaneously by a high speed framing camera and a streak camera through perpendicular observation ports. The streak camera, shown in Fig. 3, consisted of a 85-mm lens L_1, which formed an image of the arc on the plane of slit S. The slit was located at the midplane of the image of the interelectrode gap, and the slit width was adjusted to 0.1 mm by observing the diffraction pattern projected when illuminating the slit with a HeNe laser. A 55-mm lens L_2, produced a 1:1 image of the slit onto a strip of 35-mm film attached on the outer perimeter of a 10-cm diameter drum. The drum was rotated at a constant velocity of 3000 rpm by a $\frac{3}{4}$-hp electric motor. The above setup produced a temporal dispersion of 1.57 cm/ms, and a temporal resolution of about 6 μs. Adequate exposures could be obtained for peak currents greater than 10 kA with the following parameters: L_1, $F/16$; lens L_2, open; film, Kodak Tri-X developed in D-19 at 24°C for 1.5 min. High speed cine photographs were taken with a commercial Fastax camera. The line-of-sight of the Fastax was adjusted so as to look down at a slight angle at the cathode surface. Normally framing rates of approximately 1300 s^{-1} were utilized.

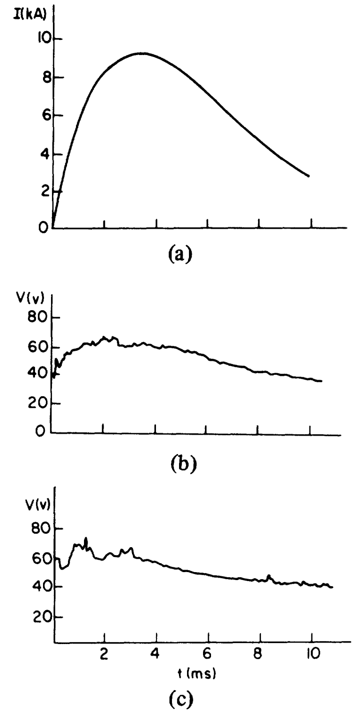

Fig. 2. Current I, and voltage V, waveforms as a function of time t, for 200-V initial capacitor voltage. (a) Current. (b) Arc voltage, with external magnetic field of 6.5×10^{-6} T/A. (c) Arc voltage without external magnetic field.

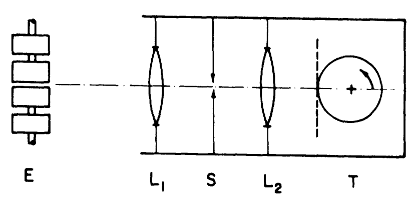

Fig. 3. Schematic drawing of streak camera.

The following procedure was followed in conducting experiments. Before commencing a test series, about ten arcs at 3.5-kA peak current were run to clean up the electrodes, without recording data. After the clean-up arcs, usually three tests were conducted at capacitor charge voltage of 100 V (peak current, 3 kA) and then the charge voltage was raised in increments of 50 V. When recording data, the following sequence was followed: 1) The capacitor bank was charged and isolated from its charging circuit, and the streak camera motor was energized. 2) The Fastax camera was energized, and allowed to come up to the desired speed. A timing circuit then pro-

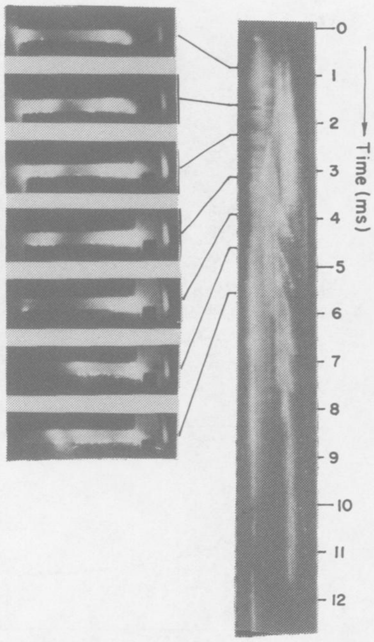

Fig. 4. Streak and frame photography of the arc with external magnetic field. Peak values for current and magnetic field are 9.3 kA and 0.06 T, at 2.9 ms, respectively. Initial capacitor voltage 200 V.

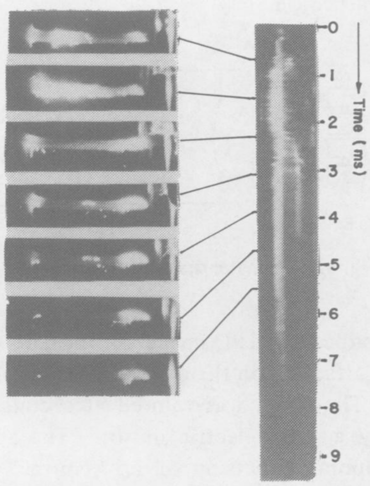

Fig. 5. Streak and frame photography of the arc without external magnetic field. Peak current is 9.3 kA at 2.9 ms. Initial capacitor voltage 200 V.

TABLE I
INTERPRETATION OF THE PHOTOGRAPHS PRESENTED IN FIG. 4

Time (ms)	Arc Characteristics	Arc Current (kA)	Arc Velocity (m/s)	Radial Magnetic Field (T)
0 - 0.5	A single column situated at trigger region	0 - 3.0	—	0 - 0.02
0.5-2.0	A diffuse arc region near the trigger with two separate arc columns. Random motion in two tangential directions in the diffused region.	3.0-8.0	—	0.02-0.052
2.0-3.0	Three arc colums; two stationary, the third is moving in the Amperian sense.	8.3-9.3	30	0.052-0.059
3.6	One of the stationary columns disappears.	9.1	—	0.059
3.6-4.3	The remaining stationary column starts to move in the Amperian direction. In addition, a diffuse arc region exists near the trigger.	9.1-8.6	32	0.059-0.056
4.3-6.7	The moving column extinguishes and a new one repeats its motion. This phenomenon repeats itself twice. No change is observed at the diffuse arc region.	8.6-6.4	32,29	0.056-0.047

TABLE II
INTERPRETATIONS OF THE PHOTOGRAPHS PRESENTED IN FIG. 5
(ZERO MAGNETIC FIELD)

Time (ms)	Arc Characteristics	Arc Current (kA)	Arc Velocity (m/s)
0 - 0.5	Arc concentrated near the trigger	0 - 3.0	—
0.5-0.8	Diffuse arc region near the trigger.	3.0-5.0	—
0.8-2.0	Four arc columns are produced. The diffuse arc disappears. An anode spot is generated.	5.0-8.0	—
2.0-3.0	Two arc columns extinguish; one of the two remaining columns executes oscillatory motion.	8.0-9.3	—
3.0-4.0	A third arc column appears while one of the previous two disappears. The new column extinguishes gradually.	9.3-9.6	—
4.-10.	Only one arc column remains.	9.3-3.0	—

duced a pulse to trigger the arc trigger circuit. 3) The trigger circuit simultaneously triggered the digitizing transient recorder, and fired the arc trigger, initiating the main arc discharge. 4) At the conclusion of each test the arc voltage was recorded on chart recorder, and the film developed.

III. Experimental Results

A. *Qualitative Behavior*

Typical streak and frame photographs of the arc with and without magnetic field are shown in Figs. 4 and 5, respectively. In both cases peak currents were 9.3 kA and the capacitor bank was charged initially to 200 V. Peak magnetic field for the arc shown in Fig. 4 was 6.05×10^{-2} T. In Tables I and II the interpretations of the fast photographs shown in Figs. 4 and 5 are summarized, listing the number of stationary and moving arc columns or the appearance of diffuse discharge as function of time. In Figs. 2(b) and (c) we present arc voltage as function of time for the two above mentioned cases. The general behavior of the arc may be characterized by a number of stages, dependent on the imposition of an external field.

In the following paragraphs a qualitative description of the various stages will be presented.

1) Arc in 6.5×10^{-6} T/A Radial Field: Three principle stages of development are noted for the arc with an external radial field of 6.5×10^{-6} T/A:

a) Arc formation: During the first 0.5 ms after triggering, the arc is concentrated in the region of the trigger. (See Fig. 4 at $t = 0$.) In the higher current arcs a very rapid jiggling of the arc in the vicinity of the trigger is often observed.

b) Diffuse arc: In the time period 0.5-1.0 ms the arc appears to be diffused around a large portion of the electrode perimeter centered about the trigger. It seems that the arc

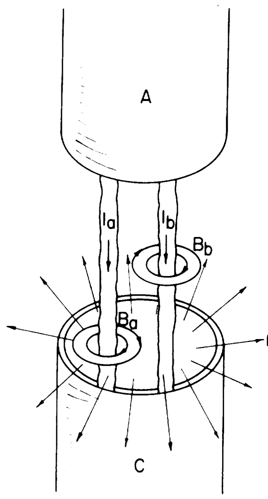

Fig. 6. Magnetic field configuration in the vicinity of two neighboring columns. Field acting on I_a is weaker than that acting on I_b. I_a moves first. A-anode, C-cathode, Bext (external magnetic field), B_a (field generated by current I_a), B_b (field generated by current I_b).

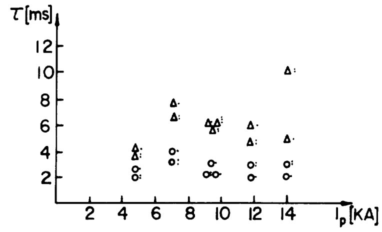

Fig. 7. Time τ from arc initiation to beginning of first arc column motion (○) and to the motion of last stationary arc column (△), plotted as function of I_p, peak arc current.

spreads simultaneously in both the Amperian and retrograde directions. The arc voltage during this stage is relatively high and noisy. In the higher current arcs narrow horizontal stripes occasionally appear on the streak camera photographs. This stage has a shorter duration for arcs having higher peak currents. Examples of stage b appear in Fig. 4.

c) Split arc: From 0.5 to 3.0 ms after arc initiation a number of separate arc columns (typically 3-6) are formed scattered about the perimeter of the electrodes. The transition from stage b to c is usually distinct. Occasionally, however, part of the discharge would coalesce into columns, while another part remained diffuse. Each separate arc column is constricted and appears to be emitted from a concentrated collection of cathode spots. The formation of the separate arc columns is usually accompanied by a reduction of arc voltage. The separate arc columns stand stationary for about 1-5 ms. In the higher peak currents arcs, the columns remain stationary longer, and separate anode spots seem to form. At some point in time some of the arc columns may disappear, and others may begin to move in the positive Amperian direction with velocities in the range 5-35 m/s. Eventually all of the remaining columns will be in motion.

d) Arc column movement: Generally the total arc motion is short, typically 1-5 cm. Arc motion over a path larger than half the arc perimeter was never observed. The arc would often be observed to travel a short distance, appear to extinguish, and then reappear at its initial position, retrace its first path, and continue in a cylical manner for several repetitions.

It is interesting to note that in cases where one column would begin to move before a neighboring column, that the column located in the weaker total radial magnetic field moved first, contrary to what one would expect intuitively. The weaker field results from the partial cancellation of the external radial field by the field produced by the neighboring arc columns, as illustrated in Fig. 6.

In addition to the stages listed above two other observations are worth noting. i) Bright spots on the exterior side surface of the anode are occasionally observed, especially for currents greater than 8 kA. These spots are apparently caused by arcing from the chamber wall (connected electrically to the cathode) to the exterior of the anode, as suggested by the presence of cathode spots on the chamber wall, and the relatively weak intensity of interelectrode arc, as seen on the streak photographs. ii) Occasionally very fine streaks, typically at an angle of 20° with respect to the discharge axis are seen on the streak photographs, especially at the edges of the electrodes. The streaks represent a radial motion (both inward and outward) with a velocity of 15 m/s. A possible cause of these fine streaks is radiation from incadescent droplets of the electrode material.

2) Arc Without a Radial Magnetic Field: In order to differentiate between phenomena caused by the cylindrical electrode geometry, and those caused specifically by the radial field, observations also were made on the behavior of the arc between the cylindrical electrodes, without the presence of the radial magnetic field. The arc behavior also can be characterized by three stages, corresponding approximately to stages a–c in the previous section. Stages a and b are qualitatively identical. The arc in stage c, however, gives the appearance of being more concentrated both in terms of a smaller number of arc column, and in terms of how evenly the columns were distributed over the electrode circumference, than in the presence of the radial magnetic field. No directed arc motion is observed, but occasionally very rapid, small amplitude, random jittering of the arc position is observed (Fig. 5, 2-3 ms). The random velocity is in the range of 100-1000 m/s. Also, in about 60 percent of the arcs observed, transverse stripes appear on streak photo, accompanied by noise in the arc voltage waveform, similar to the phenomena noted in stage b.

3) Arc in 4.0×10^{-6} T/A Radial Field: The behavior of the arc in a 4.0×10^{-6} T/A radial magnetic field was intermediate between the behavior in the 6.5×10^{-6} T/A field, and with no field. The arc was characterized by the three stages as in the case of the stronger field, but in stage d the arc motion was quite slow, so that accurate measurements of the velocity were not possible.

B. Quantitative Behavior

1) Commencement of Arc Motion: In the presence of the 6.5×10^{-6} T/A radial magnetic field, the individual arc columns move. The times, from arc initiation to i) the commencement of motion for the first arc column to move, and ii) the time when all remaining arc columns move, are plotted in Fig. 7. On the average, event i) occurs at 2.6 ms (with a

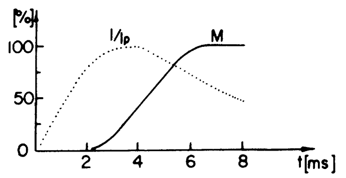

Fig. 8. The ratio M between the number of moving columns and total number of arc columns, and I/I_p, the ratio between the momentary current and peak current, as function of time.

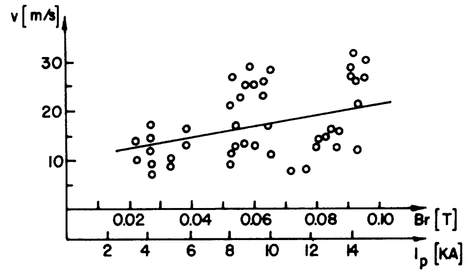

Fig. 9. The velocity of arc columns as function of peak current I_p, or peak magnetic field B_r.

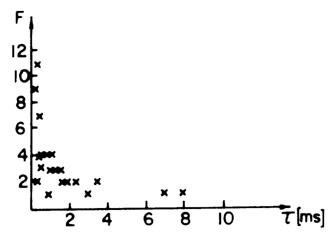

Fig. 10. The number of cyclic repetitions of arc columns F as function of τ, the duration of a single arc column movement.

standard deviation of 0.38 ms) and event ii) occurs at 5.9 ms (with a standard deviation of 1.8 ms). Thus two events straddle the time at which peak current occurs (3.4 ms); at event i) the current has attained 97 percent of its peak value, while at event ii) it had declined to 87 percent of its peak value. The increase in the fraction of arc columns which are moving M, as function of time, is plotted in Fig. 8. The data suggest the possibility of some connection between the commencement of arc motion and the attainment of peak current (i.e., $di/dt = 0$), irrespective of the value of the current.

2) Arc Column Motion:

a) Arc column velocity: A plot of arc column velocity as functions of the external magnetic field is shown in Fig. 9, at the beginning of the arc motion. Velocities in the range 5-35 m/s were observed. It may be seen that the arc velocity generally increases as a function of current (and hence magnetic field) from about 10 m/s at 4 kA to 20 m/s at 14 kA, though there is a considerable amount of scatter in the data.

b) Cyclic motion: It was noted earlier (Section III-A1d) that the moving arc had a tendency to travel a short distance for a period of time τ, extinguish, and reappear and retrace its path in a cyclic manner. Shown in Fig. 10 is a plot of the number of repetitions of the cycle F as a function of τ. It may be noted that the shorter the duration of the arc motion, the more repetitions.

IV. Discussion

One of the more interesting and unique phenomena observed in this investigation is the tendency of the arc to form a number of parallel constricted arcs, each apparently generated by a concentrated group of cathode spots. The phenomena is apparently caused by the electrode geometry, since it occurs both with and without the imposition of the external radial magnetic field. This result is particularly interesting when compared to the experiment of Sherman *et al.*, [2] who studied the motion of cathode spots on butt electrodes. Their arc was ignited by a trigger located in the center of the cathode. Cathode spots which formed near the trigger moved outward, in the retrograde direction, and formed an expanding ring. Sherman *et al.* also noted a tendency for the spots to cluster, but the clusters were spread uniformly, and constricted arc columns were not noted. Given the outward similarity in current flow geometry between cathode spots located near the edge of a cup electrode, and cathode spots located on a ring on butt electrodes, it is interesting to speculate on the causes of the difference in the results, i.e., the formation of constricted columns in the present experiment. The causes may include 1) the asymmetry in triggering in the present experiment, 2) difference in electrode material (technical grade copper in the present experiment), and 3) the influence of current flow within the electrode structure, the importance of which is illustrated by the work of Barrault [3].

The results of previous studies of vacuum arc motion in magnetic fields may be characterized into three classes: 1) *Retrograde Motion.* At relatively low currents (or current densities) individual cathode spots move in the retrograde direction with a velocity generally increasing with magnetic field strength, and reaching a saturation velocity of around 30 m/s (on Cu). If gas is introduced into the discharge region, the velocity generally decreases, and if sufficient gas is present the cathode spots move in the Amperian direction. 2) *Amperian Motion.* At higher currents or current densities the arc as a whole may move in the positive Amperian direction, with velocities in the range 20-40 m/s. Interestingly, Celikatova and Lukatskaya [4] observed that the arc velocity on Cu rail electrodes decreased with increasing values of the product of current and magnetic field strength IB. 3) *Very Fast Amperian Motion.* Celikatova and Lukatskaya observed that if IB exceeds 7×10^2 A · T, a "discontinuous" mode of arc motion is observed with velocities reaching 700 m/s at $IB = 16 \times 10^2$ A · T. Higher Amperian velocities were observed by Boxman [5] on rail electrodes, and by Starr and Naff [6] in a coaxial plasma gun. The arc motion observed during stage *c* in the present work, in the presence of the radial magnetic field, resembles most closely category 2 of the previous works. While theoretical explanations have been proposed to explain categories 1 and 3 of arc motion, a theory of category 2 motion has not been published. A possible approach may be that the plasma particles generated by the collection of adjacent cathode spots in a high current density arc may play the same role that gas molecules play in reversing the cathode spot motion to the Amperian direction in category 1 arcs.

In cases where the arc travels in the Amperian direction, it would be intuitively expected that increased magnetic field strength would result in higher arc velocities. However, in a number of experiments the opposite result is observed. In stage *c* in the present experiment, those arc columns experiencing minimum radial field (due to the interaction of neighboring arc columns) are the first to begin to move. In Celikatova and Lukatskaya's experiment, when category 2 motion was observed, the velocity decreased as a function of *IB* on Cu electrodes. In Boxman's experiment, erratic arc motion, rather than pure Amperian motion, was observed when an external transverse magnetic field was superimposed in the same direction as the self-magnetic field. In the absence of a quantitative theory of vacuum arc motion in a magnetic field in general, these phenomena are without explanation.

The cyclic nature of the arc motion in stage *c* of the present experiment is equally surprising. The phenomena is somewhat similar to that observed by Boxman on rail electrodes when an external local dc-magnetic field was imposed in the opposite direction of the self-field. In that experiment the arc was trapped in the vicinity of the external field coil, until the self-field strength exceeded the external field, at which time the arc would spread to cover the rails in the Amperian direction from the coil. When the current declined, the magnetic trap would recapture the arc. A possible explanation may require consideration of vapor emission from hots spots remaining on the electrode surface, and, in the case of the present experiment, consideration of the interaction with adjacent arc columns.

V. Conclusions

The behavior of a vacuum arc between cup electrodes may be characterized by three developmental stages: a) arc formation, b) diffuse arc, and c) simultaneous concentrated arcs. In the presence of an external radial magnetic field, a cyclic motion of the individual concentrated arc columns is observed. Some of the characteristics of the arc motion resemble previous results obtained on rail geometries.

Acknowledgment

The authors gratefully acknowledge the technical assistance of H. Yaloz, and the manuscript preparation of B. Simon. This experiment was originally suggested to R. L. Boxman by Prof. P. Barkan.

References

[1] R. L. Boxman, *IEEE Trans. Electron Devices*, vol. ED-24, pp. 122–128, 1977.
[2] J. C. Sherman, R. Webster, J. E. Jenkins, and R. Holmes, *J. Phys. D: Appl. Phys.*, vol. 8, pp. 696–702, 1975.
[3] M. R. Barrault, C. R. Melbourne, and P. D. Prewett, *J. Phys. D: Appl. Phys.*, vol. 10, pp. L213–L218, 1977.
[4] S. M. Celikatova and I. A. Lukatskaya, "Electrode material effect on vacuum arc movement in transverse magnetic field," in *Proc. XI Conf. Phenomena in Ionized Gases*, Prague, 1973, p. 80.
[5] R. L. Boxman, *J. Appl. Phys.*, vol. 48, pp. 1885–1890, 1977.
[6] W. L. Starr and J. T. Naff, "Acceleration of metal-derived plasmas," in *Plasma Acceleration*, S. W. Kash, ed. (1960), pp. 47–59.